National Aeronautics and
Space Administration

Lunar Hydrogen Infrastructure

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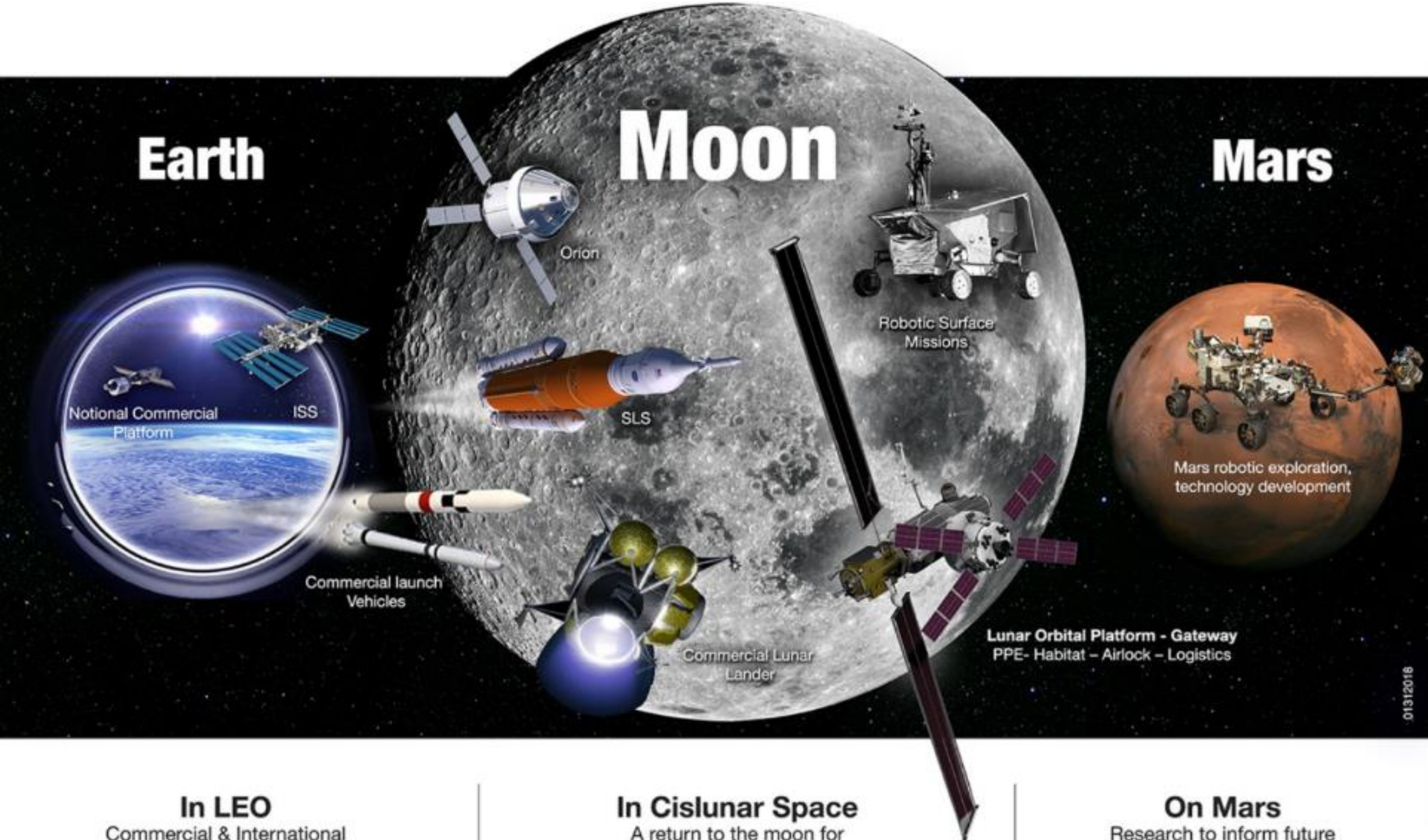
Presentation Overview

- NASA
- Logistics of Space Exploration
- Hydrogen Applications in Space
  - Propulsion
  - Power and Energy
  - Material Processing
- *In situ* Resource Utilization (ISRU)
  - Lunar Resources
  - Excavation Processes
- Economics of a Lunar Hydrogen Economy
- Discussion

NASA Overview and Objectives



In LEO
Commercial & International partnerships

In Cislunar Space
A return to the moon for long-term exploration

On Mars
Research to inform future crewed missions

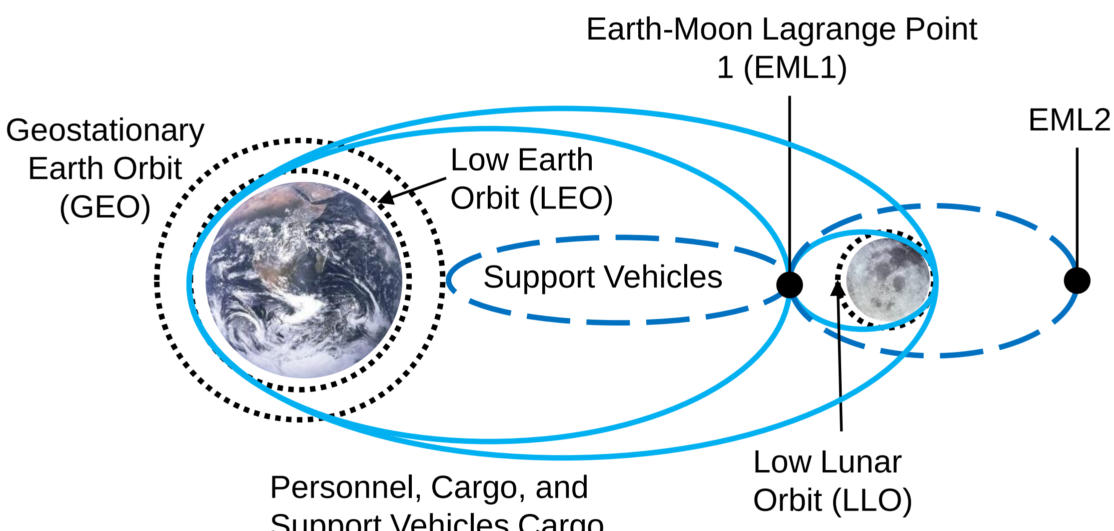
Space Exploration Logistics

- Enable exploration by staging required resources in forward locations
  - Earth Orbit (LEO, GEO)
  - LaGrange Points (EML1 and EML2)
  - Lunar Orbit
  - Lunar Surface

- Resources include propellant depots, propellant production facilities (initially H_2 and O_2), and consumable storage

- Gateway is the first element of the exploration infrastructure

Gateway with Orion Service Module



Conceptual Crewed Lunar Outpost with production facilities

Cis-Lunar Space

Lagrange Points of the Earth-Moon System as viewed from above the Earth-Moon Orbital Plane

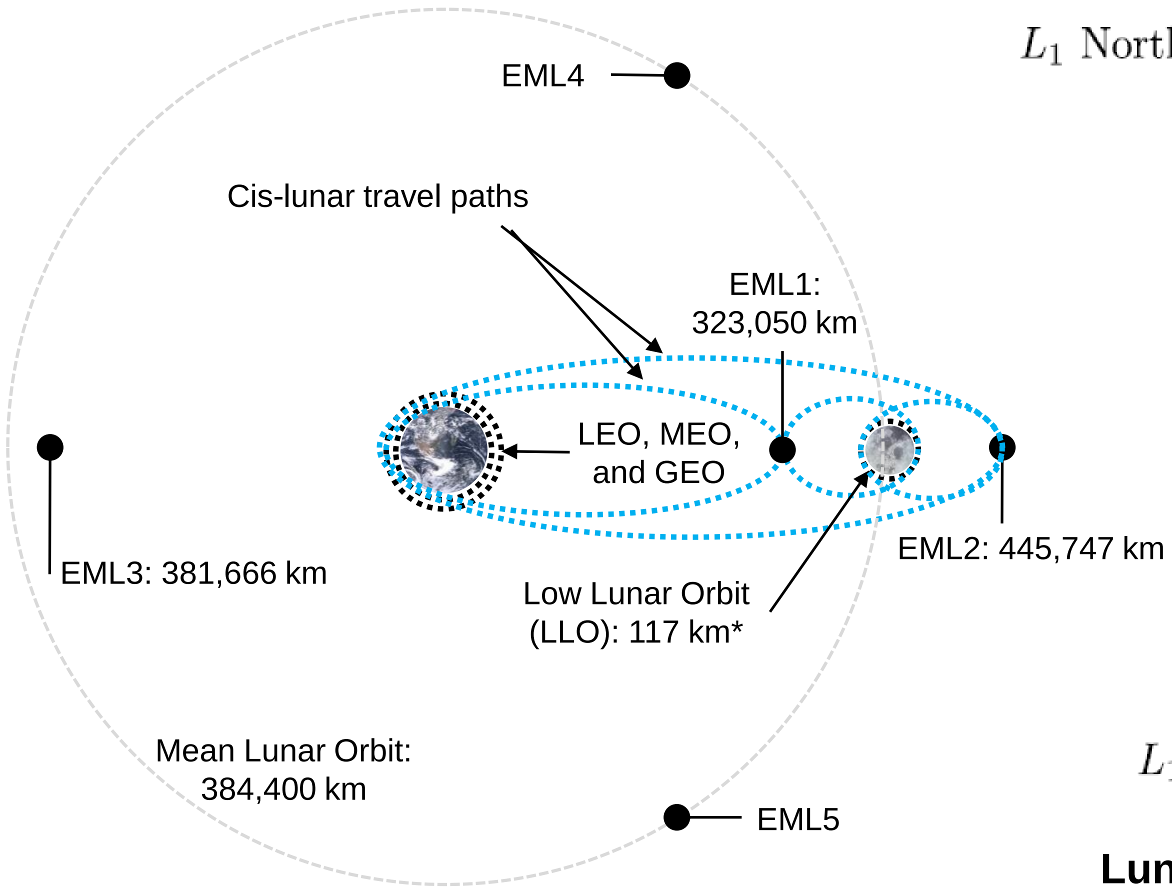
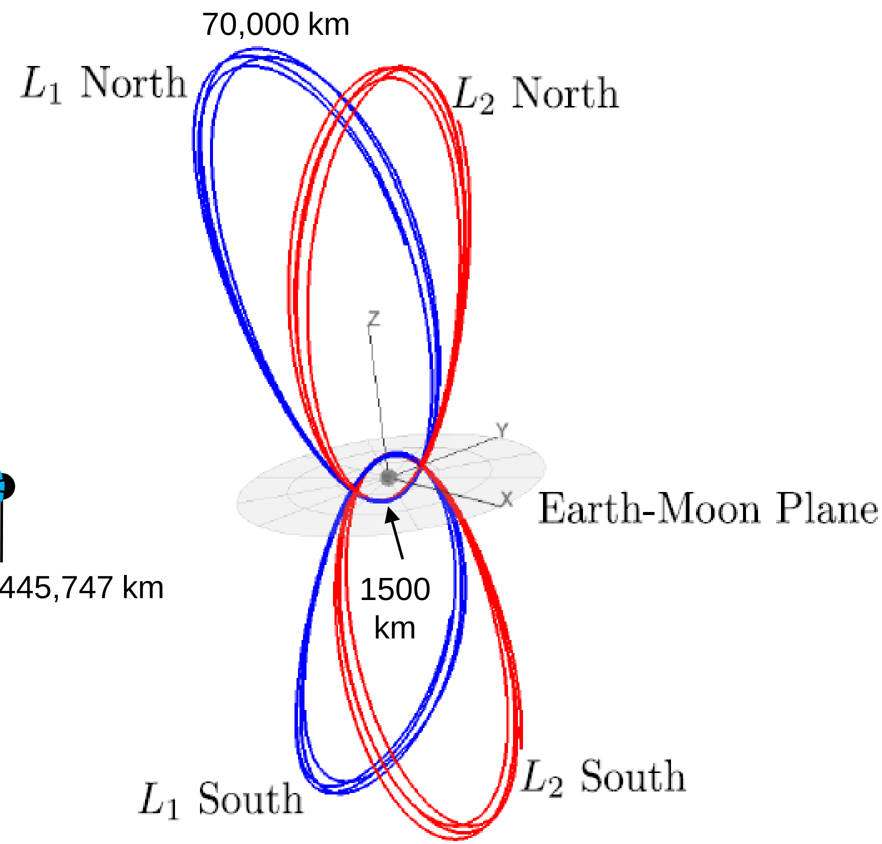


Image Not to Scale

Diameter of Earth: 12,742 km
Diameter of the Moon: 3,474 km
Low Earth Orbit (LEO): <2,000 km
Medium Earth Orbit (MEO): 2000 km to 35,786 km
Geostationary Earth Orbit (GEO): 35,786 to 42,000 km

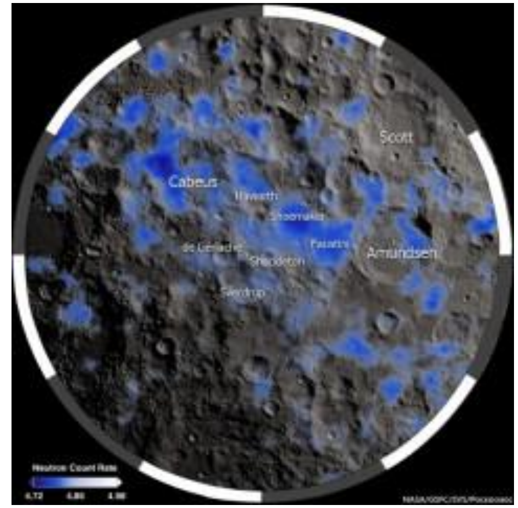


Lunar Near Rectilinear Halo Orbits (NHRO) as viewed from a Moon-Centric Inertial Frame of Reference

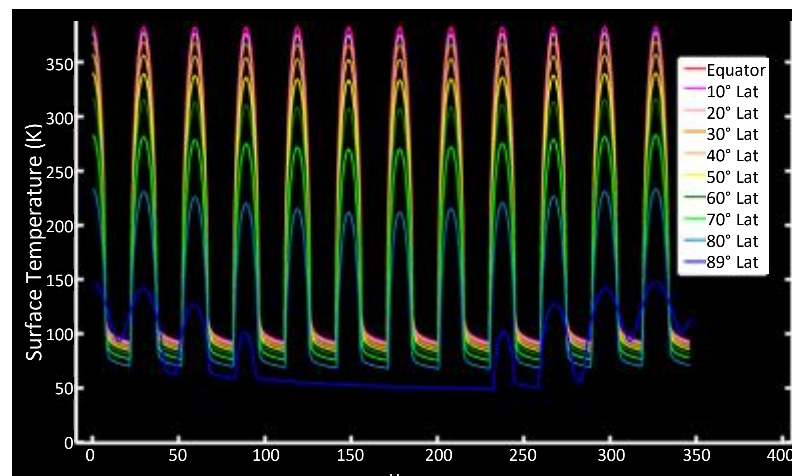
Image Source:
UTILIZING THE DEEP SPACE GATEWAY AS A PLATFORM FOR DEPLOYING CUBESATS INTO LUNAR ORBIT. Fisher, Kenton R; NASA JSC. Deep Space Gateway Science Workshop 2018 (LPI Contrib. No. 2063)

Lunar Hydrogen Infrastructure

- Lunar Hydrogen Infrastructure: Producing a needed commodity from local resources. This is a sub-set of *in situ* resource utilization (ISRU)
- ISRU enables persistent, large scale activities beyond Earth by reducing the **cost** of operating in space, on the moon, or Mars by providing a resource "**gear ratio**"
- Propellant generation concept currently is based on electrolyzing water recovered from lunar deposits of ice.



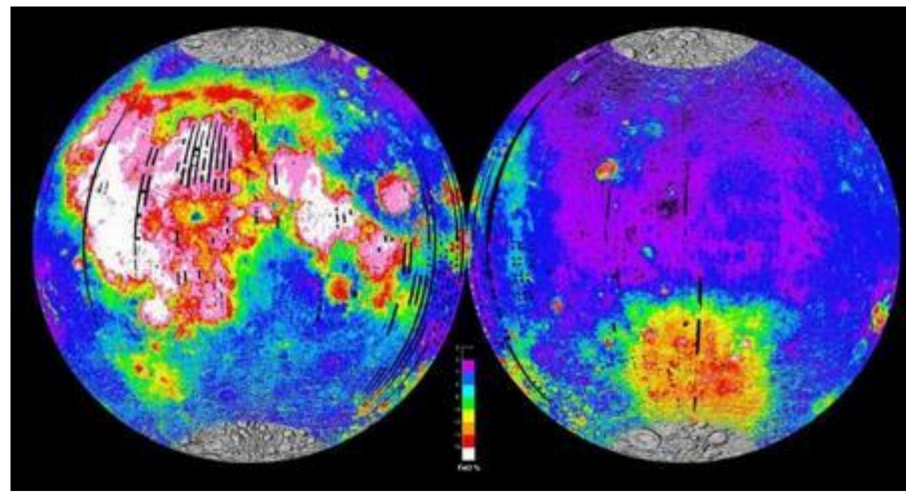
Regions likely to have water ice deposits on the Moon's south pole as identified by the NASA Lunar Reconnaissance Orbiter (LRO). Source: NASA / Goddard Space Flight Center



Average Temperature over a Lunar Day by latitude
Source: Lunar Reconnaissance Orbiter (LRO) Diviner Instrument

Space Hydrogen Applications

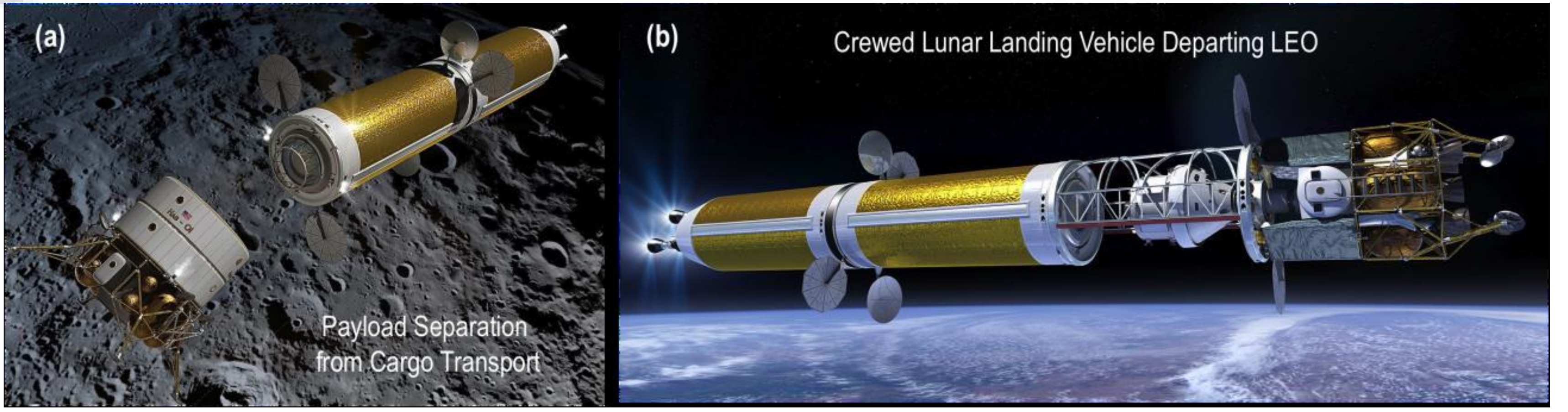
- Propulsion
  - Propellant
- Power and Energy Storage
  - Primary fuel cells
  - Regenerative fuel cells
- Material Processing
  - Reducing oxides
    - Refine metals
    - Release oxygen
    - Create water
  - Reacting with waste materials to generate plastic precursors



Global map of the iron concentration on the lunar surface created from data collected by the Clementine mission. Colors represent 2% increments of increasing FeO concentration from black (0%) to white (16%).
Source: NASA/Clementine

Carnegie-Mellon University / NASA Scarab Rover powered by a H_2/O_2 Fuel Cell System

Hydrogen: Propellant



Conceptual Reusable Lunar Transfer Vehicles: a) Cargo and b) Crewed Lunar Landing

Gateway with Orion Service Module

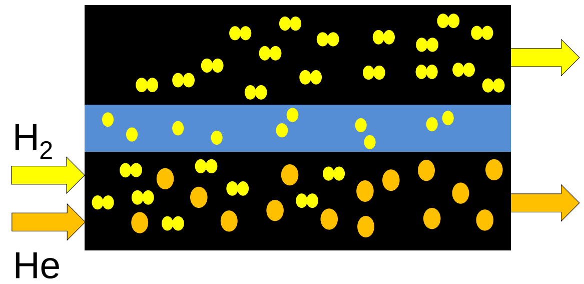
Space Launch System

Developmental Engine Under Test

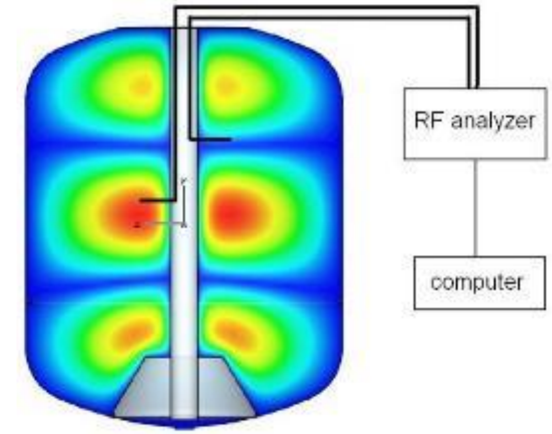
Hydrogen: Propellant

Control Issues

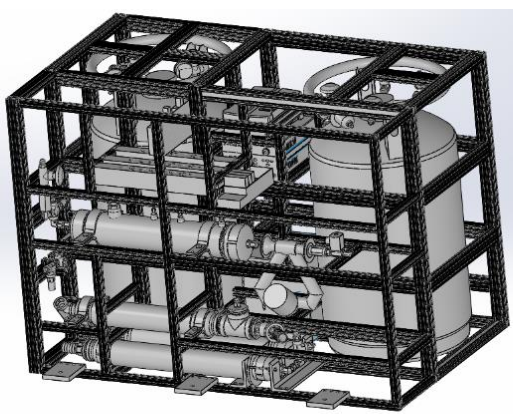
- Purity
- Level Sensing
- Cryogenic Transfer
- Cryogenic Stability



H_2 Purification and Recovery

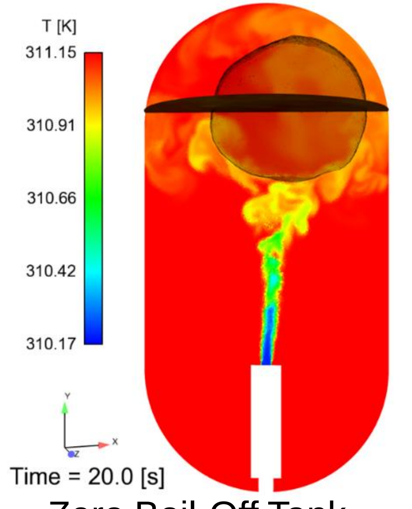


Radio Frequency Mass Gauge (RFMG)



Cryogenic Tank-to-Tank Transfer Experimental Set-up

CryoFILL Liquefaction and Storage



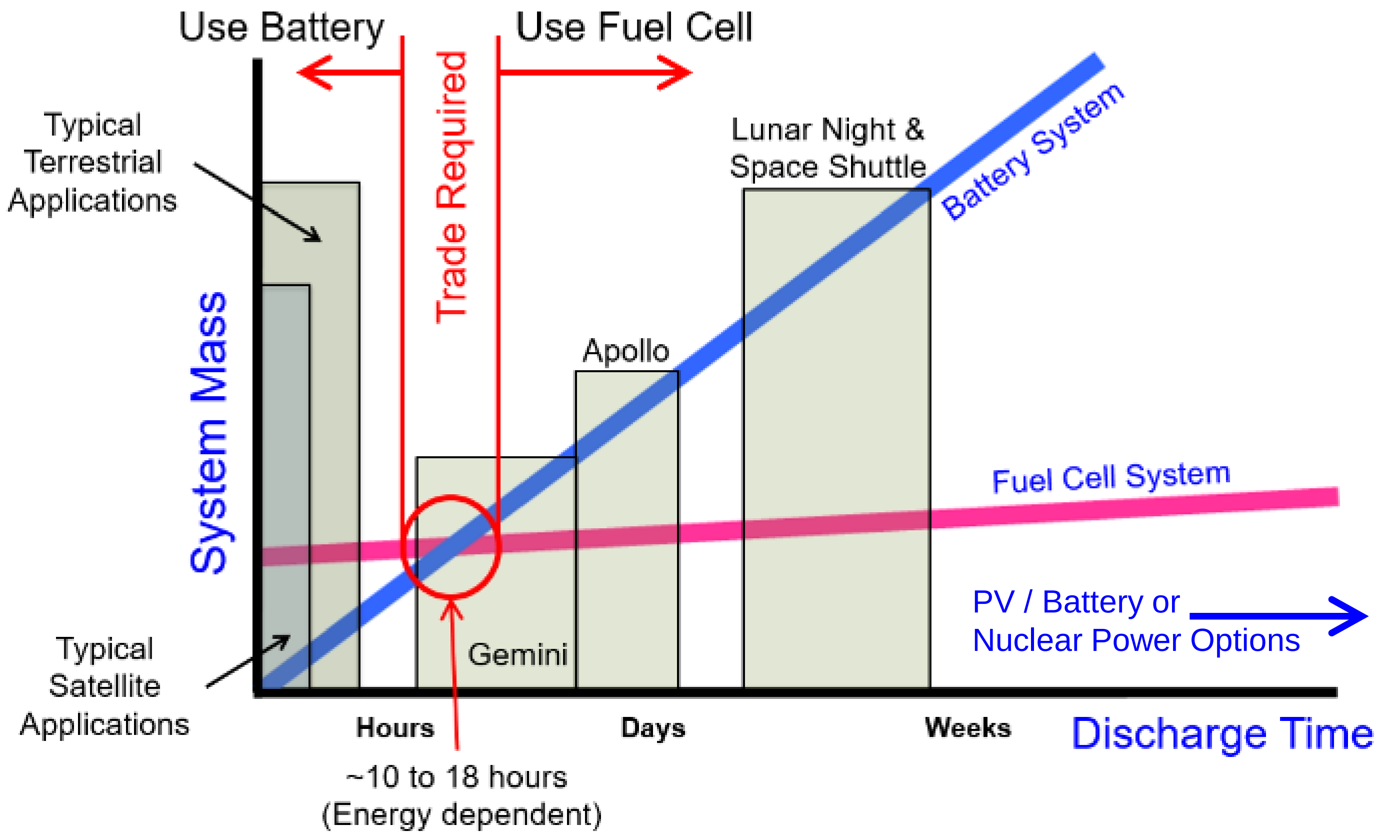
Zero Boil-Off Tank (ZBOT) Experiment

Multiple power technologies compose the Lunar Surface Power Architecture

- Solar photovoltaic systems generate power when illuminated
- Nuclear and radio isotope power systems provide constant power independent of sunlight
- Batteries meet energy storage needs for low energy applications
- Regenerative fuel cells provide high energy storage requirements especially where nuclear power may not be an option (e.g. in locations near humans)

Hydrogen: Power and Energy

Venus Explorer



Rovers

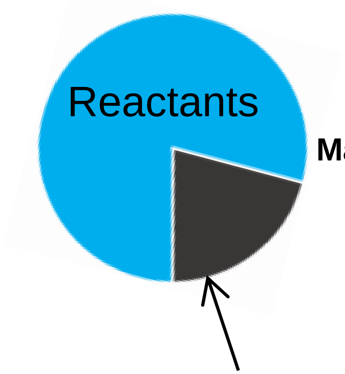
Europa Lander

Landers

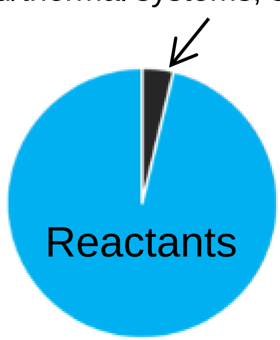
Crewed Lunar Habitats

Energy Storage Comparison

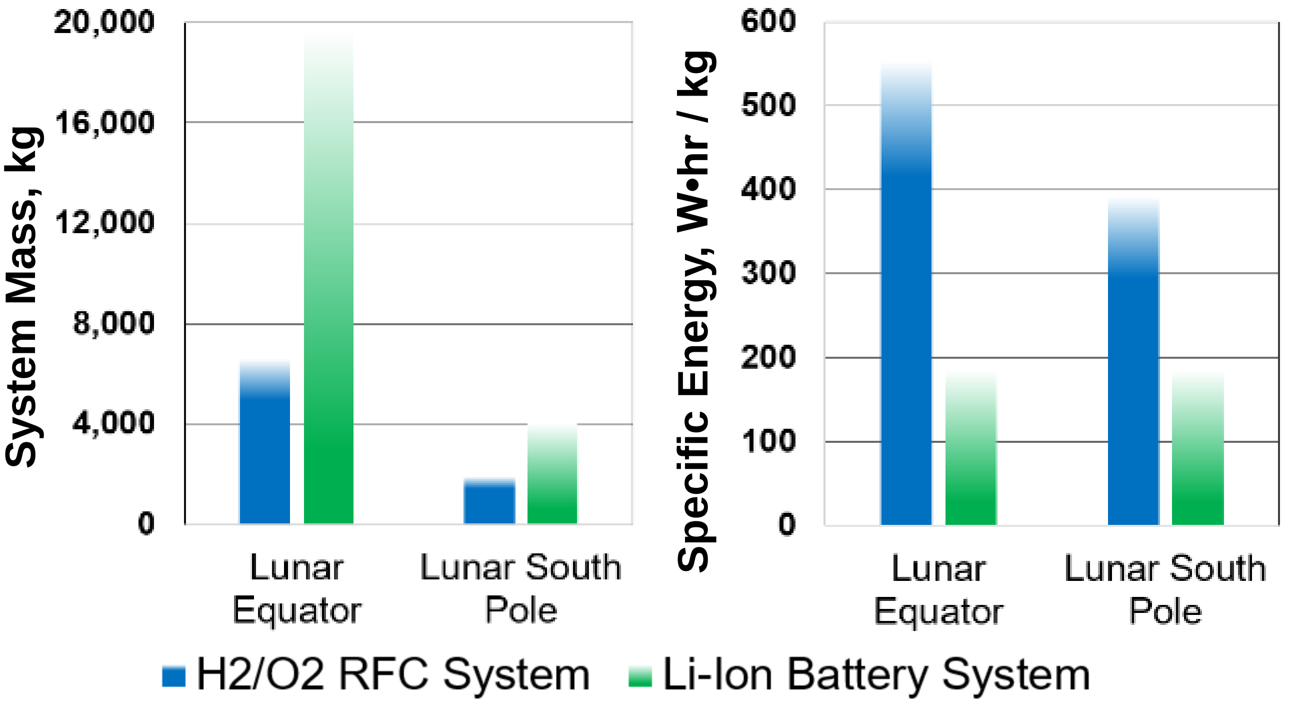
H_2/O_2 Regenerative Fuel Cell System



All other elements: stacks, fluid/thermal systems, structure, etc.



Comparing Energy Storage Options for a 10 kW Crewed Lunar Outpost Power System



Net Energy Storage by Site

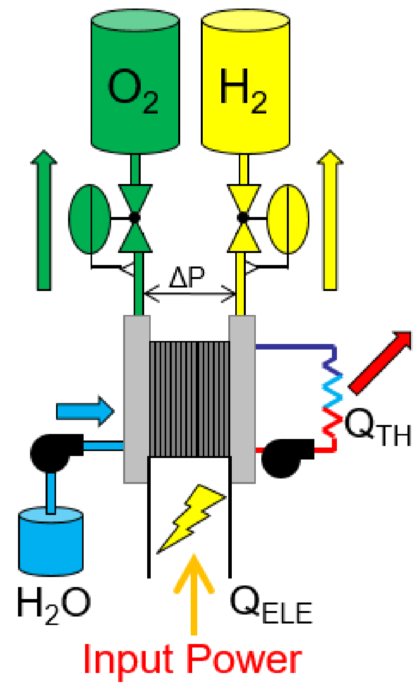
Lunar Equator = 3.64 MW•hr

Lunar South Pole = 0.75 MW•hr

Battery specific energy independent of location.
RFC specific energy dependent on location-specific parameters.

Water Electrolysis

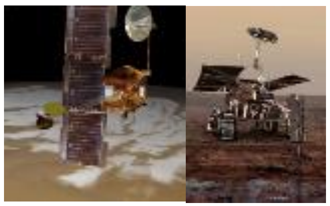
- Fundamental Process: $2H_2O + 4e^- \rightarrow 2H_2 + 2O_2$
  - Electrochemically dissociating water into hydrogen and oxygen
- Multiple pressure ranges
  - Low pressure (< 1.73 MPa (<250 psi)):
    ISRU (Propellants) and Life Support (Outpost)
  - High pressure (12.4 to 20.7 MPa (1800 to 3000 psi)):
    Energy storage and Life Support (EVA)
- Multiple Chemistry Options
  - Alkaline, Polymer Electrolyte Membrane (PEM), Solid Oxide
- Life Support:
  - Outpost: Process H_2O to generate breathing oxygen for crew
  - Extra Vehicular Activities (EVA): Stored oxygen for crew activities away from the Outpost or supporting vehicle(s)
- Energy Storage: Active chemistry in a regenerative fuel cell system
- ISRU: Process recovered H_2O to utilize H_2 and O_2



What is *In Situ* Resource Utilization (ISRU)?

ISRU involves any hardware or operation that harnesses and utilizes 'in-situ' resources to create products and services for robotic and human exploration

Resource Assessment (Prospecting)



Assessment and mapping of physical, mineral, chemical, and water resources, terrain, geology, and environment

Resource Acquisition

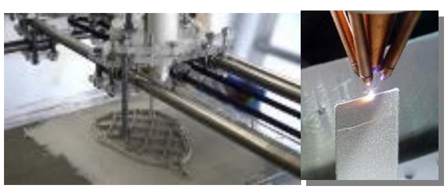
Excavation, drilling, atmosphere collection, and preparation/ beneficiation before processing

Resource Processing/ Consumable Production

Extraction and processing of resources into products with immediate use or as feedstock for construction & manufacturing

- Propellants, life support gases, fuel cell reactants, etc.

In Situ Manufacturing



Production of replacement parts, complex products, machines, and integrated systems from feedstock derived from one or more processed resources

In Situ Construction

Civil engineering, infrastructure emplacement and structure construction using materials produced from *in situ* resources

- Radiation shields, landing pads, roads, berms, habitats, etc.

In Situ Energy

Generation and storage of electrical, thermal, and chemical energy with *in situ* derived materials

- Solar arrays, thermal storage and energy, chemical batteries, etc.

- **'ISRU' is a capability involving multiple elements to achieve final products** (mobility, product storage and delivery, power, crew and/or robotic maintenance, etc.)
- **'ISRU' does not exist on its own.** By definition it must connect and tie to users/customers of ISRU products and services

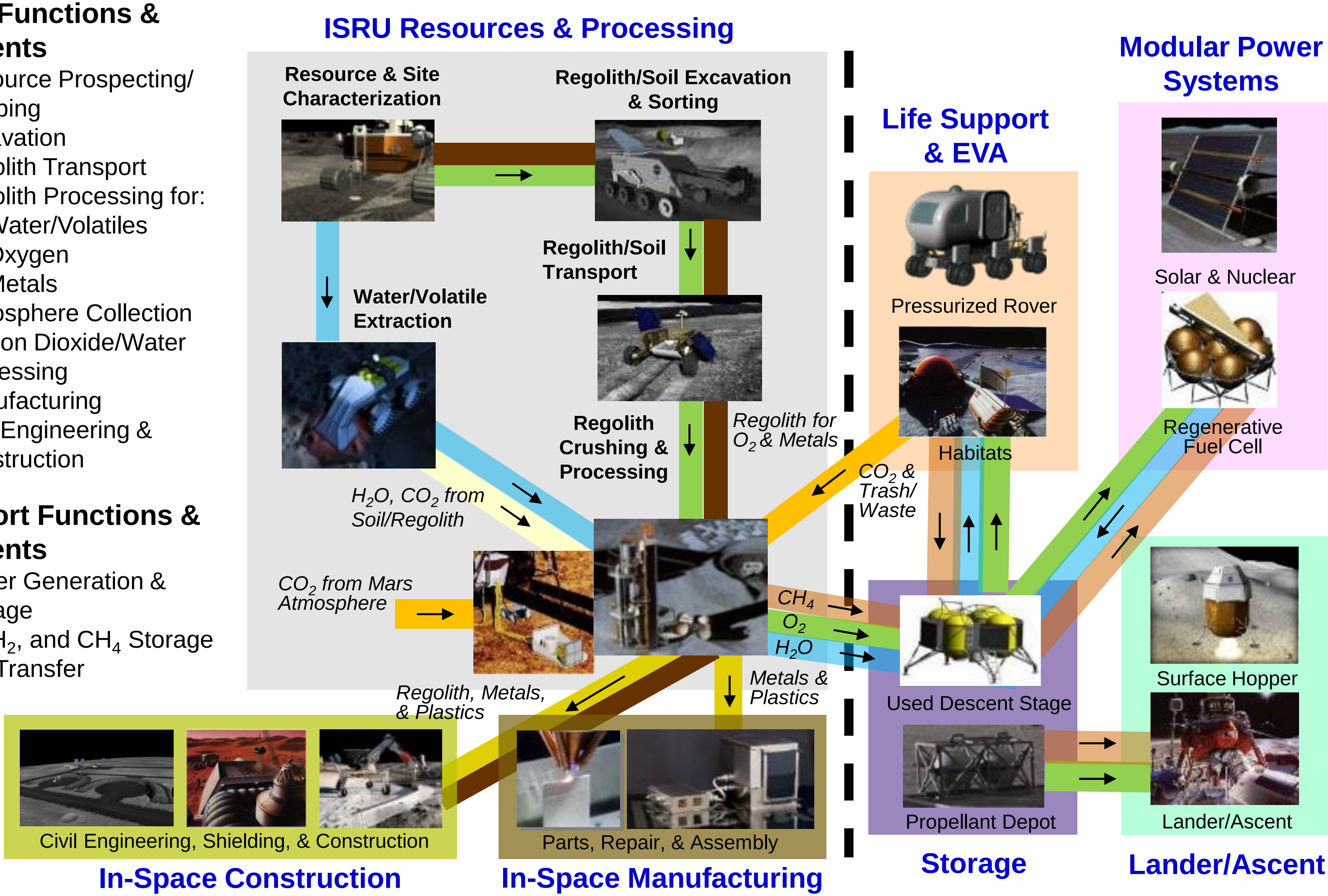
ISRU Integrated with Exploration Elements
(Mission Consumables)

ISRU Functions & Elements

- Resource Prospecting/ Mapping
- Excavation
- Regolith Transport
- Regolith Processing for:
  - Water/Volatiles
  - Oxygen
  - Metals
- Atmosphere Collection
- Carbon Dioxide/Water Processing
- Manufacturing
- Civil Engineering & Construction

Support Functions & Elements

- Power Generation & Storage
- O_2, H_2, and CH_4 Storage and Transfer



Lunar Resources and Propellant Options

Four major resources on the Moon:

Propellant Options — Extracted / Processed

REGOLITH

Ilmenite - 15%

$FeO \cdot TiO_2$	98.5%

Pyroxene - 50%

$CaO \cdot SiO_2$	36.7%
$MgO \cdot SiO_2$	29.2%
$FeO \cdot SiO_2$	17.6%
$Al_2O_3 \cdot SiO_2$	9.6%
$TiO_2 \cdot SiO_2$	6.9%

Olivine - 15%

$2MgO \cdot SiO_2$	56.6%
$2FeO \cdot SiO_2$	42.7%

Anorthite - 20%

$CaO \cdot Al_2O_3 \cdot SiO_2$	97.7%

Oxidizer: **Oxygen (O_2)**
Fuel: Aluminum

Other: Silicon + H_2 → Silane (SiH_4)

SOLAR WIND VOLATILES (Apollo Data)

Hydrogen (H_2)	50 - 150 ppm
Helium (He)	3 - 50 ppm
Helium-3 (^3He)	10^{-2} ppm
Carbon (C)	100 - 150 ppm

Oxidizer:
Fuel: Hydrogen (H_2)

Other: Carbon + H_2 → **Methane** (CH_4)

POLAR/NEA VOLATILES

Carbon Monoxide (CO)	5.7%
Hydrogen (H_2)	1.4%
Water/Ice (H2O)	5.5%
M^3 OH/H_2O	0.1 to 0.8% on surface
LAMP H_2O Frost	1 to 2% on surface
Mini SAR	Potential ice sheets

Oxidizer: → **Oxygen**
Fuel: **Hydrogen (H_2)**

Water → **Hydrogen**
Carbon Monoxide + H_2 → **Methane**

TRASH/WASTE

Plastic/packaging
Food/Plant/Bio Waste
Carbon Structures

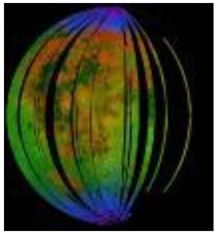
Fuel:
Hydrogen

Carbon/Carbon Dioxide + H_2 → **Methane**

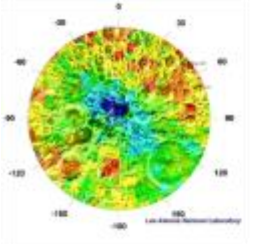
Global Assessment of Lunar Volatiles

Apollo Samples

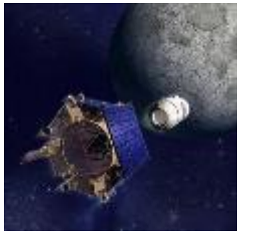
Moon Mineralogical Mapper (M^3)



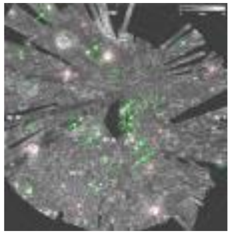
Lunar Prospector Lunar Recon Orbiter (LRO)



Lunar Crater Observation & Sensing Sat. (LCROSS)



Clementine Chandrayaan LRO Mini SAR/RF

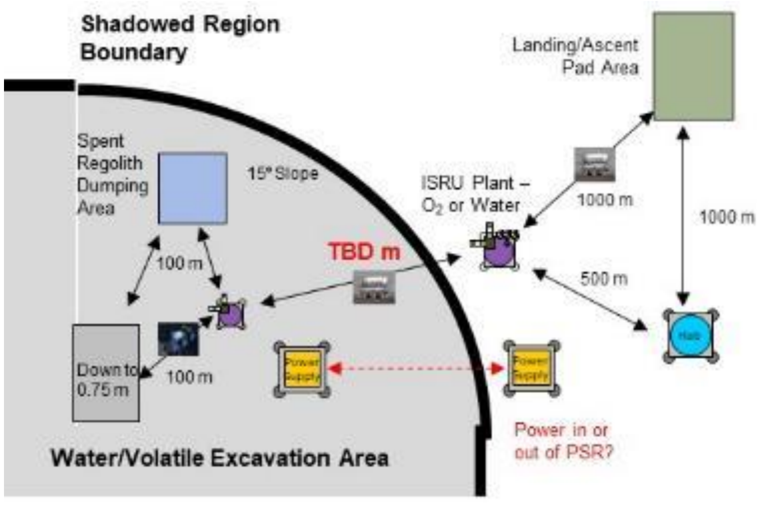


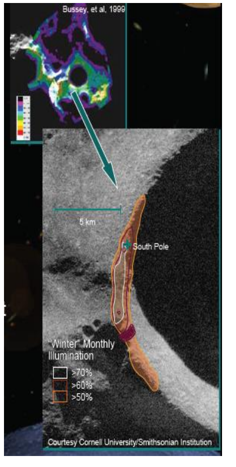
	Solar Wind	**Core Derived Water**	**Water/Hydroxyl**	**Polar Volatiles**	**Polar Ice**
Instrument	Apollo samples Neutron Spectrometer	Apollo samples	M3/DIVINER	LCROSS	Mini SAR/RF
Concentration	Hydrogen (50 to 150 ppm) Carbon (100 to 150 ppm) Helium (3 to 50 ppm)	0.1 to 0.3 wt % water in Apatite 0 to 50 ppm water in volcanic glass	0.1 to 1% water; 1-2% frost in shadowed craters	**3 to 10% Water** equivalent Solar wind & cometary volatiles **(CO, CO_2, H_2, NH_3, organics)**	Ice layers
Location	Regolith everywhere	Regolith; Apatite	Upper latitudes	Poles	Poles; Permanent shadowed craters
Environment	Sunlit	Sunlit	Low sun angle Permanent shadow <100 K	Low or no sunlight; Temperatures sustained at <100 K	<100 K, no sunlight
Depth	Top several meters; Gardened	Top 10's of meters	Top mm's of regolith	Below 10 to 20 cm of desiccated layer	Top 2 meters

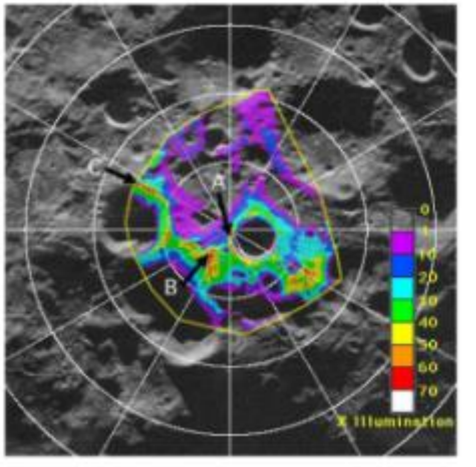
Lunar Locations and ISRU

Polar Locations – *Optimal location for sustained surface operations*

- Areas of near permanent sunlight (>70% sunlight per year)
  - Lower thermal extremes and greater use of solar power
  - Regolith based resources for oxygen and metals; Highland regolith (iron poor)
- Areas of permanent shadow
  - Cold locations for cryogenic storage, instruments, and thermal energy generation
  - Polar volatiles may include hydrogen, water, ammonia, carbon monoxide, and organics

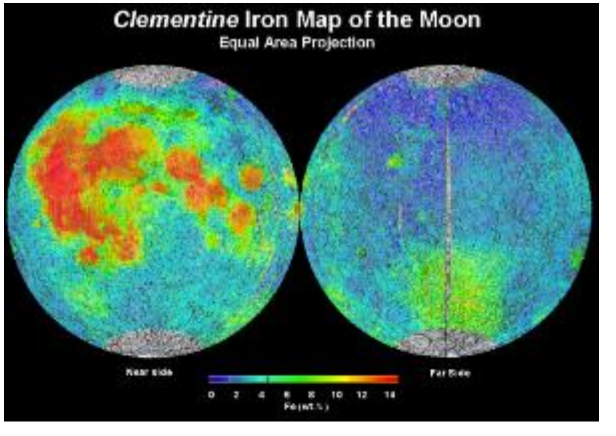




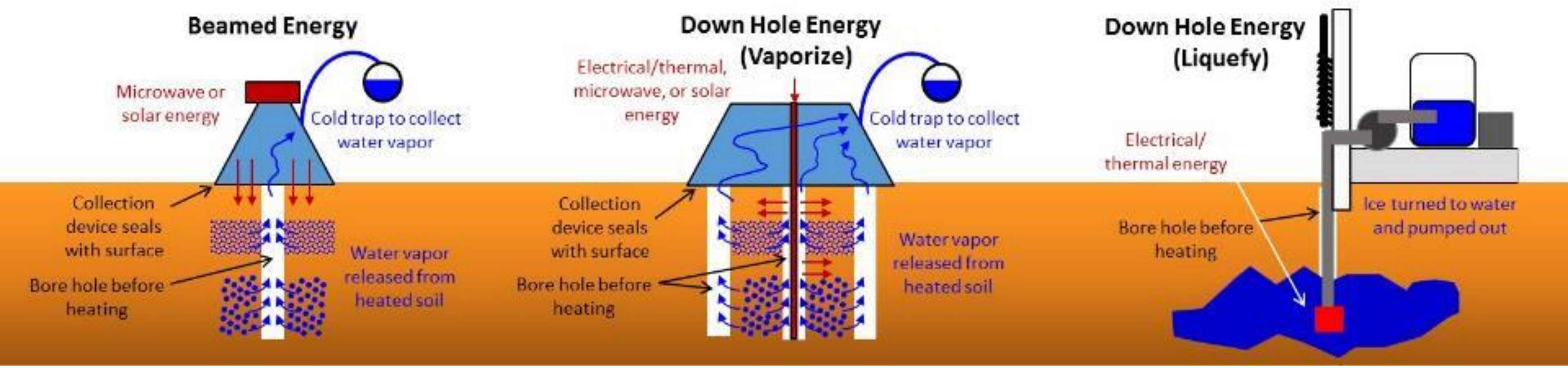


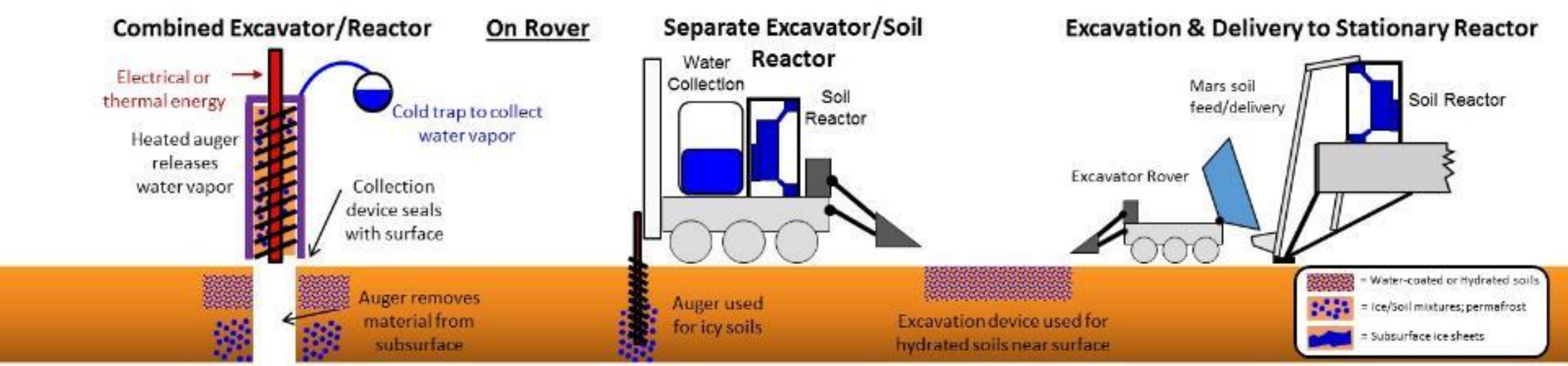
Equatorial Locations

- Equal day/night durations (~14 days)
- Significant temperature swings from day to night
- Mare and highland material; more diverse mineral opportunities as a function of location
  - High and low Titanium mares (ilmenite and iron oxides)
  - Pyroclastic glasses (iron and water/hydrogen source)
  - KREEP (Potassium, Rare Earth Elements, Phosphorus)



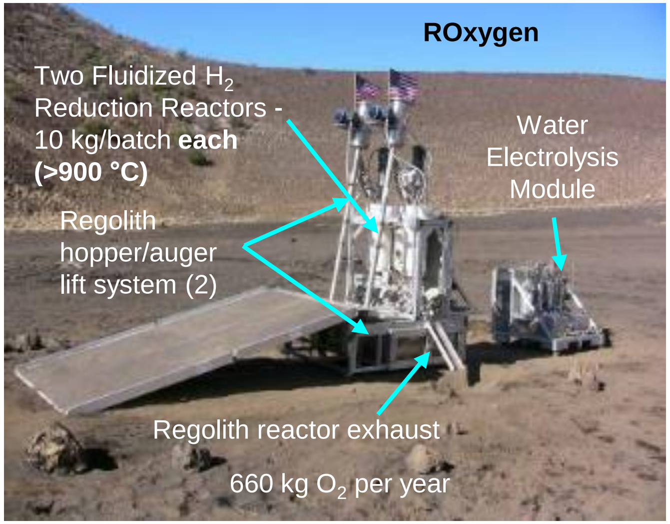
In Situ Water Extraction vs Excavation and Processing Trade Space





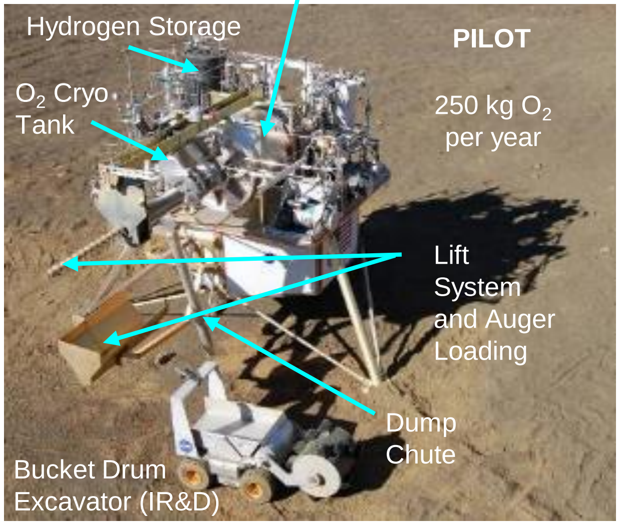
Lunar Processing – Oxygen & Metal Extraction

Hydrogen Reduction of Regolith



1. **Heat Regolith to >900 C**
2. **React with Hydrogen to Make Water**
3. **Crack Water to Make O_2**

Rotating H_2 Reduction Reactor - 17 kg/batch



Carbothermal Reduction of Regolith

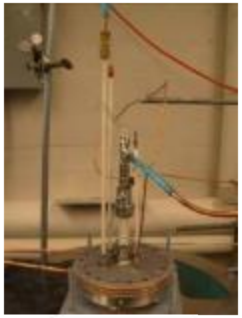
Solar Concentrator & Fiber-optic Cables

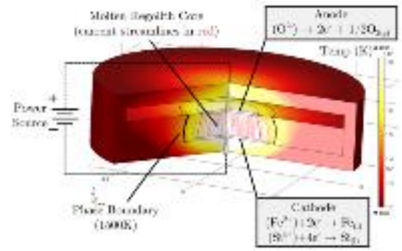
Regolith Reduction Chamber

Pneumatic Lift System and Auger Loading

1. **Melt Regolith to >1600 C**
2. **React with Methane to produce CO and H_2**
3. **Convert CO and H_2 to Methane & Water**
4. **Crack Water to Make O_2**

Molten Electrolysis of Regolith



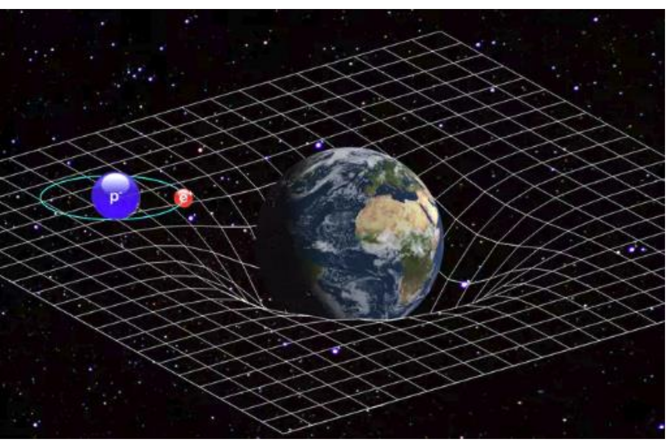


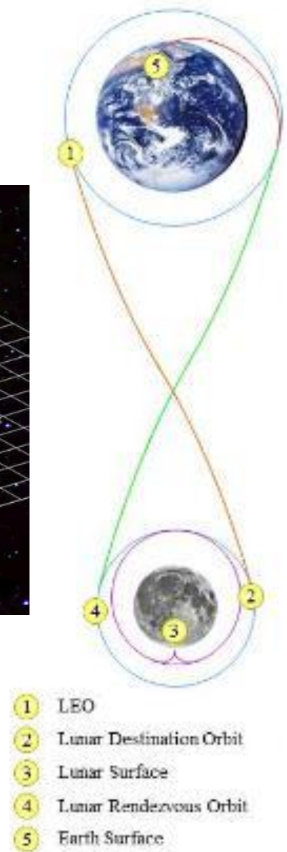
1. **Melt Regolith to >1600 C**
2. **Apply Voltage to Electrodes To Release Oxygen**

Leverage (Gear) Ratios using ISRU

Every 1 kg of propellant made on the Moon or Mars saves from 7.4 to 11.3 kg in LEO

Potential 334.5 mT launch mass saved in LEO
= 3 to 5 SLS launches avoided per Mars Ascent





A Kilogram of Mass Delivered Here…	…Adds This Much Initial Architecture Mass in LEO	…Adds This Much To the Launch Pad Mass
Ground to LEO	-	20.4 kg
LEO to Lunar Orbit (#1→#2)	4.3 kg	87.7 kg
LEO to Lunar Surface (#1→#3; e.g., Descent Stage)	7.5 kg	153 kg
LEO to Lunar Orbit to Earth Surface (#1→#4→#5; e.g., Orion Crew Module)	9.0 kg	183.6 kg
Lunar Surface to Earth Surface (#3→#5; e.g., Lunar Sample)	12.0 kg	244.8 kg
LEO to Lunar Surface to Lunar Orbit (#1→#3→#4; e.g., Ascent Stage)	14.7 kg	300 kg
LEO to Lunar Surface to Earth Surface (#1→#3→#5, e.g., Crew)	19.4 kg	395.8 kg

Economics of ISRU for Space Applications (1)

A 'Useful' Resource Depends on the Location, What is needed, How much is needed, How often it is needed, and How difficult is it to extract the resource

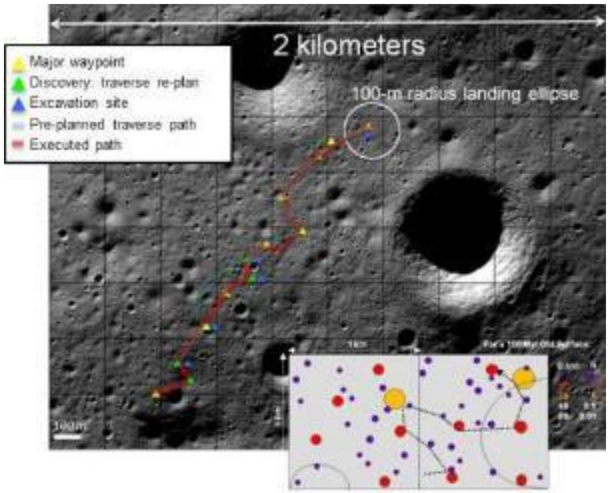
- **Location**
  - Resource must be assessable: slopes, rock distributions, surface characteristics, etc.
  - Resource must be within reasonable distance of mining infrastructure: power, logistics, maintenance, processing, storage, etc.

- **Resource extraction must be 'Economical'**
  - **Concentration and distribution of resource and infrastructure needed to extract and process the resource must allow for Return on Investment (ROI)** for:
    - Mass ROI - mass of equipment and unique infrastructure compared to bringing product and support equipment from Earth. Impacts number and size of launch vehicles from Earth
      - 1 kg delivered to the Moon or Mars surface = 7.5 to 11 kg launched into Low Earth Orbit
    - Cost ROI - cost of development and certification of equipment and unique infrastructure compared to elimination of launch costs or reuse of assets (ex. reusable vs single use landers)
    - Time ROI - time required to notice impact of using resource: extra exploration or science hardware, extended operations, newly enabled capabilities, etc.
    - Mission/Crew Safety ROI - increased safety of product compared to limitations of delivering product from Earth: launch mass limits, time gap between need and delivery, etc.
  - **Amount of product needed must justify investment in extraction and processing**
    - Requires long-term view of exploration and commercialization strategy to maximize benefits
    - Metric: mass/year product vs mass of Infrastructure
  - **Transportation of product to 'Market' (location of use) must be considered**
    - Use of product at extraction location most economical

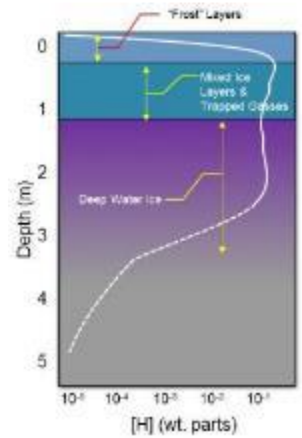
Economics of ISRU for Space Applications (2)

Need to assess the extent of the resource 'ore body'

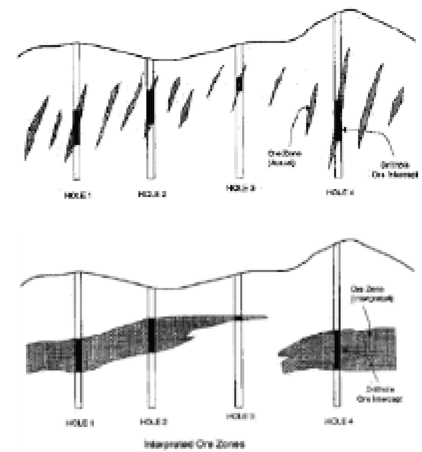
Need to Evaluate Local Region (1 to 5 km)



Need to Determine Vertical Profile



Need to Determine Distribution



Need to assess What is needed, How much is needed, How often it is needed

- **Resource Product Needs**

Location	Product	Amount (kg)	Need/Time	Use
Moon	O_2	1000	Per Year	Crew Breathing - Life Support Consumable Makeup
	O_2	3000 - 3500	2x Per Year	Non-Reusable Crew Ascent Vehicle Propulsion - Surface to Low Lunar Orbit: Earth fuel
	O_2	~16000	2x Per Year	Reusable Ascent/Descent Propulsion - Surface to L_1/L_2: Earth Fuel (4000 kg payload)
	O_2/H_2	~30,000	2x Per Year	Reusable Ascent/Descent Propulsion - Surface to L_1/L_2 (4000 kg payload)
	H_2O	150,000	2x Per Year	Lunar Human Outpost & Reusable Transportation
	O_2/H_2	150,000	Per Year	Anount needed for Propellant Delivery to LDRO for Human Mars Mission
Mars	O_2/CH_4	22,728/6978	Per Use/1x 480 Days	Non-Reusable Crew Ascent Vehicle Propulsion - Surface to High Mars Orbit
	O_2/CH_4	59,000/17,100	Per Use/1 or2x Per Yr	Reusable Ascent/Descent Propulsion - Surface to Mars Orbit
	H_2O	3,075	Surface/500 Days	Life Support System Closure
	H_2O	15,700	Per Use/1x 480 Days	Extracted H_2O to Make Non-Reusable Ascent Vehicle Propellant
	H_2O	38,300	Per Use/1 or2x Per Yr	Extracted H_2O to Make Reusable Ascent/Descent Vehicle Propellant

[green box] = Initial Requirement [red box] = Horizon Goal

Space Commercialization & Mining

Promote Terrestrial Involvement in Space & ISRU: Spin In-Spin Out

Private Industry

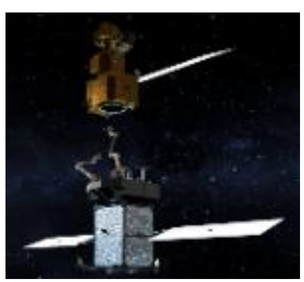
Resource Prospecting

Commercial Cargo & Crew

ULA Cislunar 1000 Vision

Use lunar derived propellants

Satellite Servicing



US Government Interest & Legislation

US Space Law & Directives

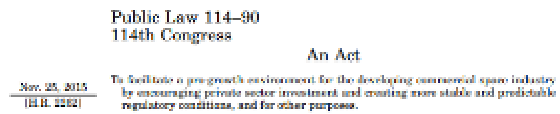
H. R. 2262—18

"CHAPTER 513—SPACE RESOURCE COMMERCIAL EXPLORATION AND UTILIZATION

"§ 51303. Asteroid resource and space resource rights

"A United States citizen engaged in commercial recovery of an asteroid resource or a space resource under this chapter shall be entitled to any asteroid resource or space resource obtained, including to possess, own, transport, use, and sell the asteroid

US Commercial Space Launch Competitiveness Act



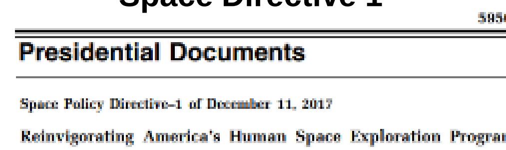
Public Law 114–90
114th Congress

An Act

Nov. 25, 2015
[H.R. 2262]

To facilitate a pro-growth environment for the developing commercial space industry by encouraging private sector investment and creating more stable and predictable regulatory conditions, and for other purposes.

Space Directive 1



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Presidential Documents

Space Policy Directive–1 of December 11, 2017

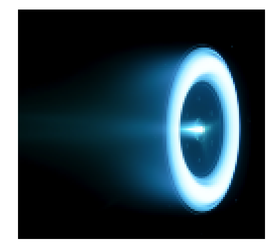
Reinvigorating America's Human Space Exploration Program

NASA NextSTEP Broad Agency Announcements

Crew habitats

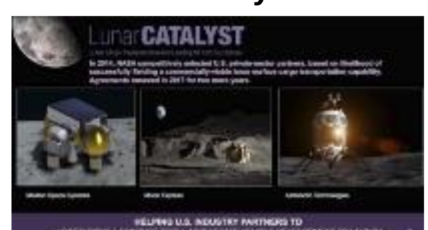
FabLab

Power & Propulsion Studies



ISRU

Commercial Lunar Payload Services(CLPS) & NASA Payloads



Presentation Overview

- NASA
- Logistics of Space Exploration
- Hydrogen Applications in Space
  - – Propulsion
  - – Power and Energy
  - – Material Processing
- *In situ* Resource Utilization (ISRU)
  - – Lunar Resources
  - – Excavation Processes
- Economics of a Lunar Hydrogen Economy
- Discussion

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National Aeronautics and
Space Administration
NASA
Thank you for your attention